DEVELOPMENT OF AN ADDITIVE MANUFACTURING COMPRESSION MOLDING PROCESS FOR LOW COST IN-HOUSE PROTOTYPING

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by

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ABSTRACT

DEVELOPMENT OF A LOW-COST COMPOSITE COMPRESSION MOLDING PROCESS

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Abstract.

Composite parts can be manufactured using various processes. Generally, a mix of resin and fiber is formed into the desired geometry using a mold and pressure. One process used by Dr. Joseph Mello in his research is known as compression molding. Compression molds are generally made from large billets of aluminum or stainless steel, are machined by a CNC mill, and are then hand-finished with polishes and mold preparation products. This process is expensive, requires large machinery and experienced operators, and introduces long lead times relative to the design cycle of the part being manufactured. The nature of Dr. Mello's undergraduate research necessitates that molds be built by undergraduates without the machining experience needed to generate G-code for metal molds, and for less cost than the traditional method.

Additive manufacturing (AM) was investigated, as it is a mold-making process that does not require CNC experience, yet can produce complex geometry. A thermoplastic AM process and material were selected, and prepreg fiber cloth was selected based on the properties of the AM plastic. Samples were made using the cloth both by a traditional molding process, using two aluminum surfaces, and using additively manufactured molds. These parts were then tested in an Instron tensile tester for tensile and shear strength. The key findings of this report are that additively manufactured PETG molds, when prepared properly, produce compression molded parts with similar strengths to parts made using aluminum molds.

ACKNOWLEDGMENTS

This project would not have been possible if it were not for the generous donation of materials by Jimmy Shedden at TenCate Composites. Dr. Xuan Wang's broad knowledge base and involvement in the advancement of Additive Manufacturing processes have been crucial in this project. Finally, I would like to personally thank Dr. Joseph Mello, who puts students first and has a passion for engineering which he transfers to his pupils.

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I. Introduction

This report will describe the development of a compression molding process suitable for forming prepreg carbon fiber using molds built using additive manufacturing techniques. Ultimately, parts built using the process were tested to determine their mechanical properties.

Prior to beginning this project, multiple parts were manufactured using the traditional method and the molds built by undergraduate researchers for Dr Mello, as shown in Figure 1 below.

Figure 1. Aluminum mold halves built by the Black Gold team for Dr Mello.

During the manufacturing, notes were made regarding difficulties encountered with the current process, lead times, and any special tools/chemicals that were required. Findings concluded that the traditional method produced quality parts and the molds would likely have a longer service life than necessary, but the process involved too many specialty tools and resources to be used for the purpose of prototyping and education. Additionally, the process of removing the heavy aluminum molds from the heated press was hazardous, and the heavy parts occupied valuable space in low-height storage.

A successful process design would allow a user to build a compression molded part without any knowledge of G-code programming for lower cost than the traditional method while retaining 60% or better of the traditionally manufactured part's strength.

II. Literature Review

Compression Molding

This project is aimed at producing a compression molding process capable of making complex composite parts without the use of CNC machining. Compression molding is a process by which a mold, usually aluminum or steel, is designed to produce a part out of either continuous fiber mixed with resin or a chopped fiber and resin mixture. These molds are heated by conduction and pressed together, typically with a hydraulic press (Fette et al.). The combination of a temperature controlled cure and the high dimensional control of rigid molds has several benefits for part design, including the ability to use a mix of reused chopped and continuous fibers in a single part (Wu et al). This hybrid technique can yield superior surface finish and dimensional stability in the finished part (Warnock).

Undergraduate Research

Dr. Mello and his students are investigating the use of compression molding to make high performance parts which use a mixture of chopped and continuous fiber to build a bicycle suspension link for a Ventana Alpino mountain bike (Tischler et al.). In the past, these molds were machined out of 6061-T6 aluminum with a Haas VF3 Mill. The molds were then finished with polishing compound and prepared with MoldWiz F-57 NC. Material cost for these molds was $300 and total machining time for each mold half was 4 hours.

Additive Manufacturing

Additive Manufacturing has developed for 30 years and has finally become affordable and simple enough that it has been adopted by hobbyists, educators, and engineers around the world (Goldberg). Additive Manufacturing processes have been used to build compression molds out of metals, particularly stainless steel (Fette et al.). The machines required to build metal molds are considered high end specialty equipment and are more expensive and rare than machining centers, and thus are not fit for use in this project.

Some AM system companies have designed products specifically for use with resin/fiber systems (Stratasys). These products are typically plastics which are strong, temperature-tolerant, and do not react with resins used in composite manufacturing. The companies that sell these filaments require their own print systems which can be many times more expensive than the enthusiast printers used by many hobbyists, small engineering firms, and research facilities. As a result, the need remains for an open-source process of composite compression molding using materials that are compatible with low-cost printers.

Additive Advantages

Using additive methods may allow for several improvements to the mold making process. Because material can be controlled in a layer-by-layer fashion, additive manufacturing allows the user to control the geometry within what would otherwise be a solid part. Software is now included in CAD suites that allows such control, and can use stress simulations to optimize this internal structure (Gardan, Schneider). A more highly optimized structure can reduce material usage, part weight, and print time. Additionally, additive manufacturing produces less waste which is easily recycled (Muthu et al)

Design Considerations for Additive Manufacturing

In order to design a mold, the material characteristics must be known. Because parts created using AM are built in a point-by-point or line-by-line manner, the mechanical properties differ from a simple solid of the same material. Analysis of these mechanical properties gives different values depending on the direction in which the sample is tested, known as anisotropy (Song et al). For the purposes of this project, anisotropy was ignored and a safety factor of 5 was used.

Environmental/Economic Analysis

The primary environmental concern is the volatile organic compound (VOC) production associated with melting thermoplastic filament. VOCs create ground-level ozone and are hazardous to humans in high concentrations. Melting filament also produces ultrafine particles, which can cause eye and throat irritation. To mitigate these effects, printers should be located in a well ventilated, sparsely populated room. (Ingarao et al.). The cost of filament is substantially greater than the cost of the power required to print, and cost should be estimated using the cost of the filament used to build a part (Franchetti et al.).

III. Design

Design Objective:
Create a low-cost composite compression molding manufacturing technique for prototyping. This process must achieve the following objectives.

- Cost less than the traditional method (~$300) to produce two molds
- Can be performed by an untrained user with a manual
- Possible without the use of proprietary filament/machines
- Produces parts which are >60% the strength of traditionally manufactured parts

Solution Approach:
Determine which alternative method is most valuable for prototyping and quantify resulting part quality.

- Select AM process and material based on decision matrix results
- Design mold and simulate to determine maximum allowable compressive force
- Print molds
- Experiment with different mold preparation processes to create a reusable, easily repeatable process
- Build parts using traditional and additively manufactured molds
- Test parts to determine if mechanical properties are consistent between traditionally built parts and parts built using the new process

	25%	30%	25%	20%	100%
Option	Resolution	System Cost	Material Cost	Ease of Use	Score
SLA	5	3	1	3	3
SLM	4	1	2	2	2.2
FDM	2	5	4	4	3.8
DLP	5	3	1	3	3

Table 1. Decision matrix used to determine which AM method is appropriate. FDM has the highest composite score and was tested.

	40%	40%	20%	100%
Option	Strength	System Cost	Material Cost	Score
PETG	2	5	4	3.6
ABS	3	4	3	3.4
ULTEM	4	0	1	1.8
Nylon 910	4	3	2	3.2

Table 2. Decision matrix used to determine which type of filament to use in the proposed FDM-based process. PETG has the highest composite score and was tested.

Item	Quantity/Dim	Cost	Supplier
Puck Mold AL 1	1.25”x3”x13”	$43	Midwest Steel & AL
Puck Mold AL 2	1.5”x3”x12”	$51	Midwest Steel & AL
Rocker Mold AL	2.5”x5”x36”	$196	Midwest Steel & AL

Table 3. Material cost table for aluminum molds used in the Black Gold senior project.

Item	Quantity/Dim	Cost	Supplier
Puck Mold AM 1	91g	$6	Ultimaker Direct
Puck Mold AM 2	84g	$6	Ultimaker Direct
Rocker Molds AM	710g	$47	Ultimaker Direct

Table 4. Material cost for Additively Manufactured molds using 60% triangular infill.

IV. Methods

Two flat plates were manufactured using PETG filament printed on an Ultimaker 3 Extended with triangular infill. One of these plates and its infill is shown in Figure 2 below. Top and bottom surfaces were compared to determine which was more flat using a machined steel gauge. The bottom surface was found to have less deviation, and was thus used as the molding surface.

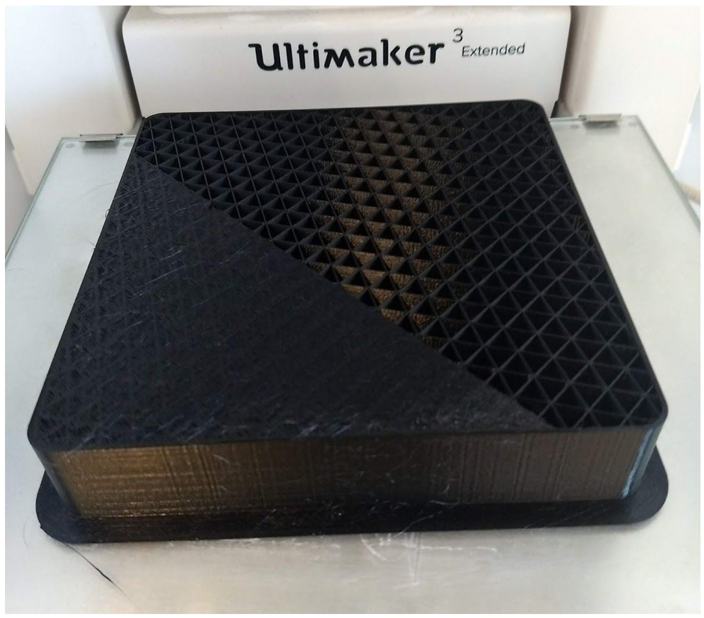


Figure 2. Additively manufactured mold half showing triangular infill.

After trial and error, a mold preparation routine was established that allowed parts to be removed easily without damaging the mold. As shown in Figure 3 below, the molds were first thoroughly degreased using lacquer thinner, with special attention to remove any oils that may have been deposited within the grooves of the surface. Next, Fibreglast 1153 Mold Release was applied generously with a light touch, allowing the liquid to dry between applications. When the ridges on the mold face have a matte sheen, indicating that mold release has filled the grooves, the mold is ready to dry before molding.

Figure 3. Chemicals used for preparation of additively manufactured mold.

Once the mold preparation was dry, three-ply test samples of TenCate Ambertool HX42 QISO prepreg fabric were laid onto the mold surface, shown below in Figure 4.

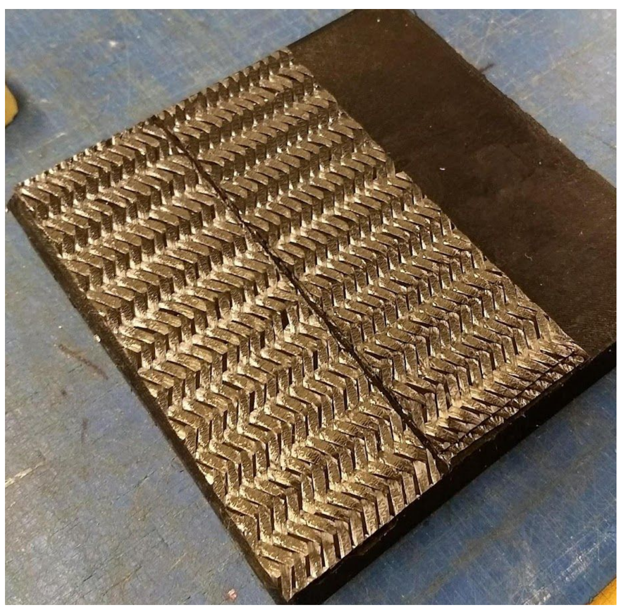


Figure 4. Prepreg layers being laid onto mold surface.

A Carver heated laboratory press was set to 150°F and the molding pressure was maintained at 25psi. After allowing the resin to cure for the recommended cure cycle, shown below in Figure 5, the molding assembly was removed from the press and set under cold running water to encourage separation. This process was repeated using aluminum molds holding mold pressure, temperature, specimen geometry, and cure time constant to have parts against which these samples could be compared.

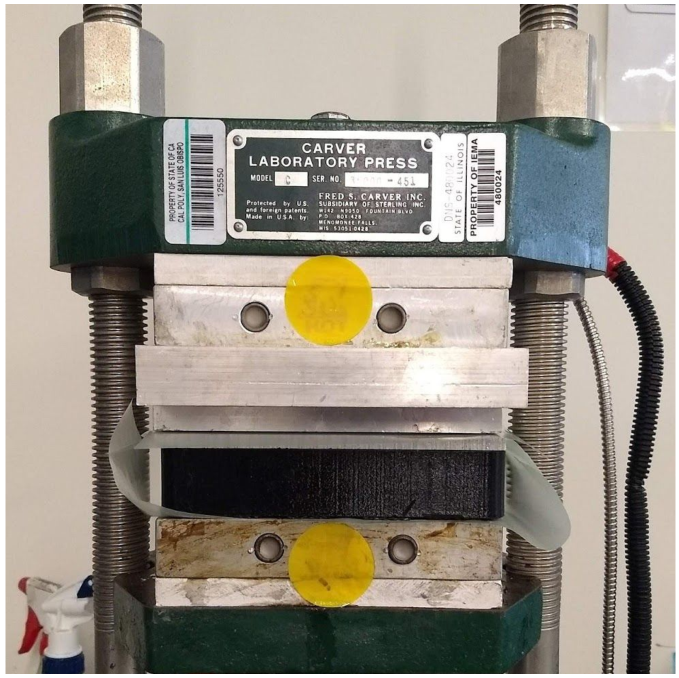


Figure 5. Carver heated laboratory press assembly with additively manufactured mold installed.

After cooling, the carbon fiber samples were removed from the mold with a dull spatula, depicted below in Figure 6.

Figure 6. Test specimens being removed from a mold using a spatula.

The specimens were pried off using a dull spatula to prevent damaging the mold surface. After all the test specimens were built, they were put in the curing oven for the full post cure cycle, which is discussed in the "Results" section of this report. The specimens were then cut to length, creating 20 test strips from each process, and tested for tensile and shear strength in an Instron 1311 Universal Testing Machine in the configurations in Figure 7 and Figure 8 below.

Figure 7. Specimen being tested for tensile strength.

Figure 8. Specimen being tested for shear strength using a short beam shear test fixture.

In the following section will describe the statistical analysis performed on data collected using the above process.

V. Results

Tensile and shear test forces were recorded and compiled into a .csv file and were processed in JMP. As shown below in Figure 9, a oneway analysis of tensile test data was performed. A test of variances, shown in Figure 10, determined that the variances of the tensile test data was statistically equal.

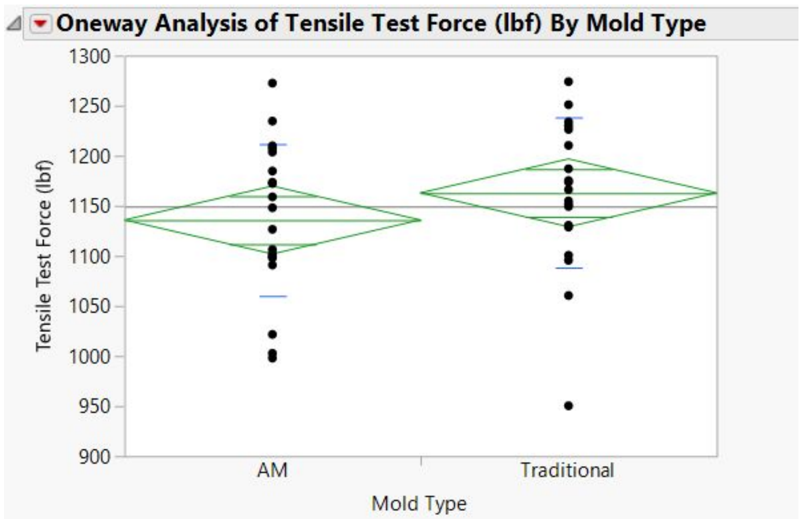
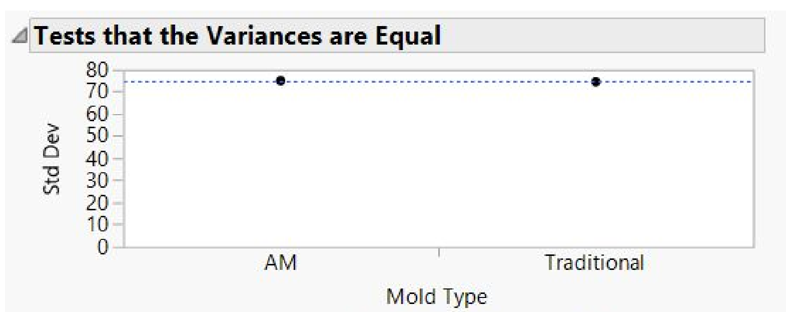


Figure 9. Oneway comparison of tensile strengths of specimens built using AM and traditional molds.



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
AM	20	75.04990	60.70500	60.70500
Traditional	20	74.56899	54.46050	54.13500

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.0006	1	38	0.9804
Brown-Forsythe	0.2016	1	38	0.6560

Figure 10. Variance test for tensile test forces.

Due to their equal variances, a simple t-test was used to determine if the mean tensile test forces were equal for both manufacturing methods. The result of this test is that the mean tensile strengths of both series of test specimens are equal, as shown in Figure 11.

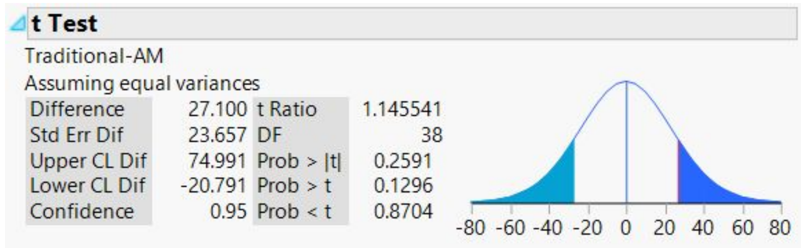


Figure 11. T-test which shows that mean tensile test forces are statistically equal for both mold materials.

The same statistical approach was applied to shear test data, as shown below in

Figure 12.

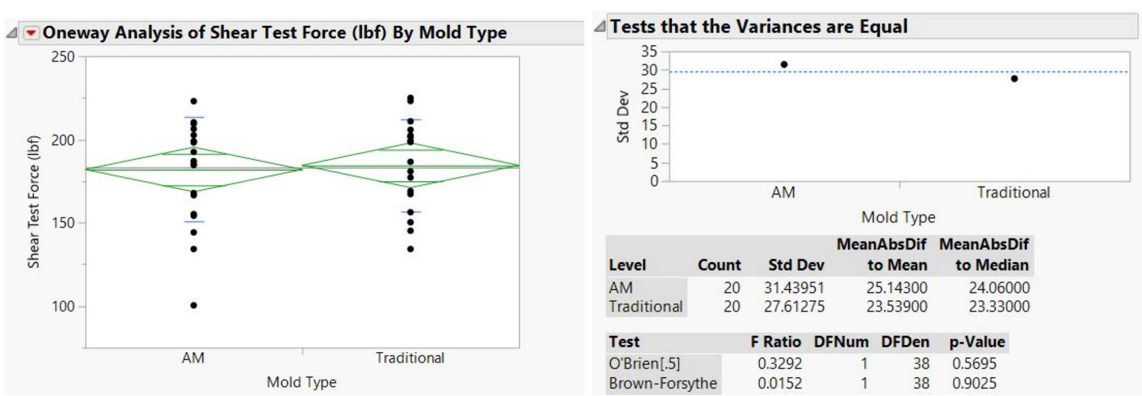


Figure 12. Oneway comparison and variance test of shear test force.

A test of variance proved that the variances were statistically equal, allowing the use of a t-test to determine whether mean shear test forces were equal. The results of this t-test are shown below in Figure 13.

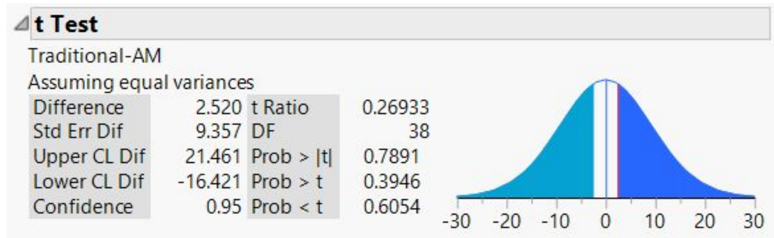


Figure 13. T-test which confirms that shear strengths are equal for both mold materials.

The results of the statistical testing conclude that the use of PETG molds and Fibreglast 1153 mold release did not have an effect on the tensile or shear strength of specimens made of TenCate Ambertool HX42 QISO prepreg carbon fiber. By using a mold prep product and not plastic bagging, part surface finish and fiber orientation is better preserved and the process is more easily repeated.

Despite the success of the mechanical property testing, this method introduces some serious problems that may reduce the utility of this process.

The low working temperature of PETG, or any other filament that can be used with a hobbyist 3D printer, prevents the high molding temperature which is typically used in compression molding. As a result, the resin used in the prepreg cloth must cure at low temperatures. As shown below in Figure 14, the fastest possible initial cure with Ambertool resin is a 6 hour cycle.

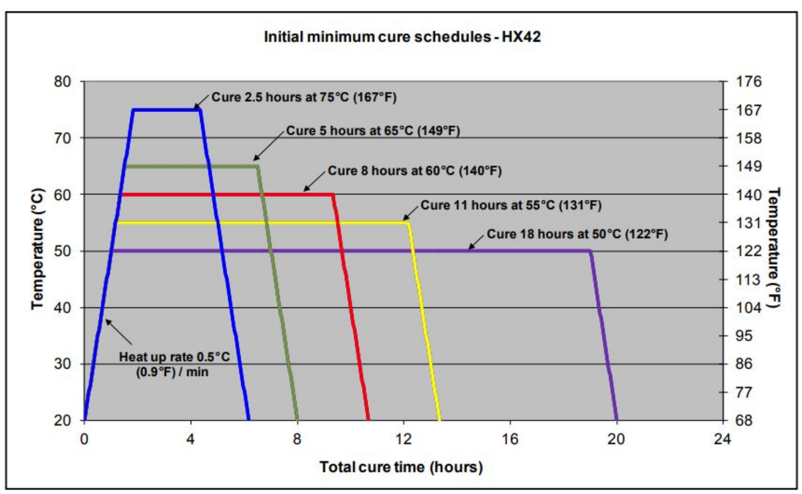


Figure 14. Initial cure schedules for low-temperature Ambertool resin used in this project.

In addition to the long initial cure cycle, the manufacturer recommends postcuring using the 16 hour schedule shown below in Figure 15.

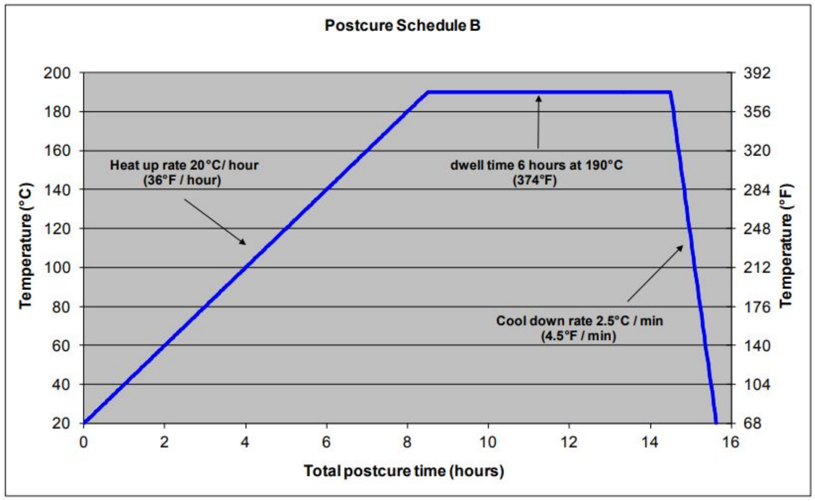
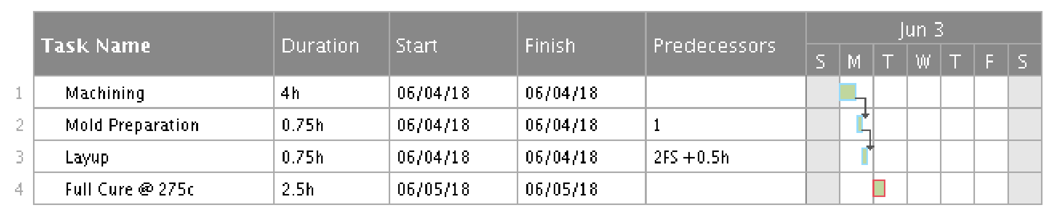
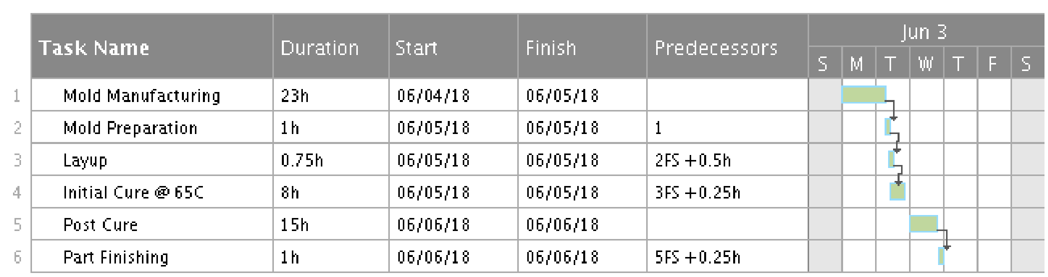


Figure 15. Postcure schedule for Ambertool resin.

Long cure and postcure times increase lead time for parts built using this process, and these changes in lead time factor into the usability of the process. Shown below in Figure 16 are two Gantt charts comparing the manufacturing time for a mold and part built using both traditional and AM processes.



	Task Name	Duration	Start	Finish	Predecessors
1	Machining	4h	06/04/18	06/04/18	
2	Mold Preparation	0.75h	06/04/18	06/04/18	1
3	Layup	0.75h	06/04/18	06/04/18	2FS +0.5h
4	Full Cure @ 275c	2.5h	06/05/18	06/05/18	



	Task Name	Duration	Start	Finish	Predecessors
1	Mold Manufacturing	23h	06/04/18	06/05/18	
2	Mold Preparation	1h	06/05/18	06/05/18	1
3	Layup	0.75h	06/05/18	06/05/18	2FS +0.5h
4	Initial Cure @ 65C	8h	06/05/18	06/05/18	3FS +0.25h
5	Post Cure	15h	06/06/18	06/06/18	
6	Part Finishing	1h	06/06/18	06/06/18	5FS +0.25h

Figure 16. Gantt charts showing manufacturing flows for both traditional and AM processes.

A fishbone diagram was created to analyze the root causes of the long manufacturing time of these parts when compared to traditionally molded parts, which are usually finished within 2 hours. As seen below in Figure 17, the key factors that contribute to long lead times come down to the properties of the resin used in this project.

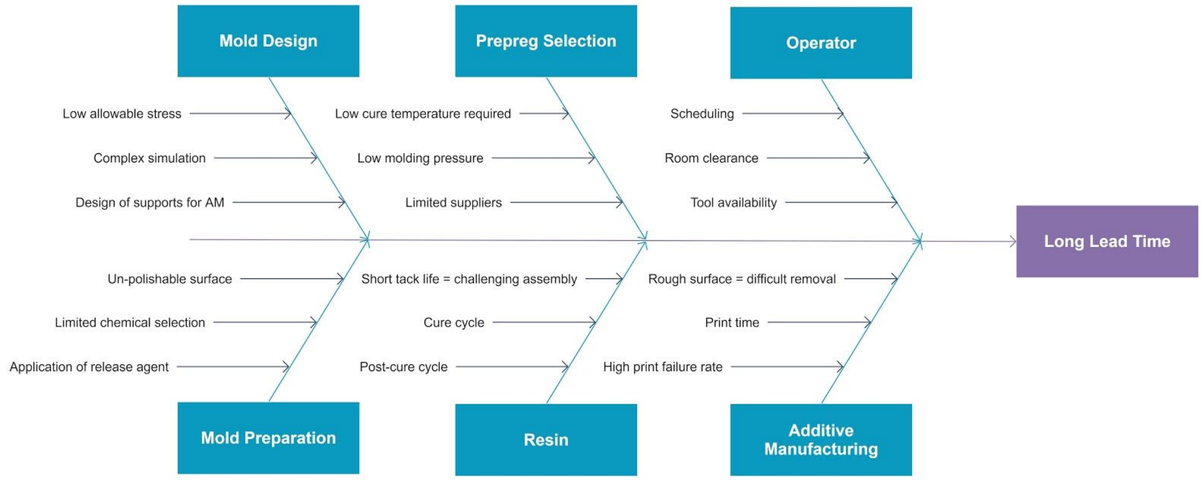


Figure 17. Fishbone diagram of the factors leading to long lead times using the process described in this report.

VI. Conclusion

This project introduces a process for using additively manufactured molds for composite compression molding. Through testing and statistical qualification, this project confirmed that parts molded directly off of additively manufactured molds have the same tensile and shear strength as parts molded off of aluminum molds. Due to the low temperatures required by the plastic AM molds, the prepreg has long cure and postcure times.

The reduced cost of this process opens up the possibility of using additively manufactured molds to build parts for educational or hobby purposes. Long lead times and scheduling printers and ovens for days on end may or may not rule this process out, but that is dependent on how many students are making parts and which resins are used. One possible solution would be to use a wet layup, but this would introduce added complexity which is beyond the scope of most undergraduate composites courses.

Future research might be conducted to determine minimum allowable draft angle, dimensional accuracy of 3D printed molds, and finished part surface quality.

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